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Remote Sensing of Environment 90 (2004) 126–134

Remote Sensing of Environment

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Assessing crop residue cover using shortwave infrared reflectance

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Received 16 December 2002; received in revised form 8 May 2003; accepted 11 October 2003

Abstract

Management of crop residues is an important consideration for reducing soil erosion and increasing soil organic carbon. Current methods of measuring residue cover are inadequate for characterizing the spatial variability of residue cover over large fields. The objectives of this research were to determine the spectral reflectance of crop residues and soils and to assess the limits of discrimination that can be expected in mixed scenes. Spectral reflectances of dry and wet crop residues plus three diverse soils were measured over the 400–2400 nm wavelength region. Reflectance values for scenes with varying proportions of crop residues and soils were simulated. Additional spectra of scenes with mixtures of crop residues, green vegetation, and soil were also acquired in corn, soybean, and wheat fields with different tillage treatments. The spectra of dry crop residues displayed a broad absorption feature near 2100 nm, associated with cellulose-lignin, that was absent in spectra of soils. Crop residue cover was linearly related ($r^2 = 0.89$) to the Cellulose Absorption Index (CAI), which was defined as the relative depth of this absorption feature. Green vegetation cover in the scene attenuated CAI, but was linearly related to the Normalized Difference Vegetation Index (NDVI, $r^2 = 0.93$). A novel method is proposed to assess soil tillage intensity classes using CAI and NDVI. Regional surveys of soil conservation practices that affect soil carbon dynamics may be feasible using advanced multispectral or hyperspectral imaging systems.
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Keywords: Crop residue cover; Shortwave infrared reflectance; Soil erosion; Soil organic carbon

1. Introduction

Crop residues are the portions of a crop that are left in the field after harvest. Crop residues on the soil surface decrease soil erosion, increase soil organic matter, and improve soil quality (Lal et al., 1999). By reducing the movement of eroded soil into streams and rivers, the movement of nutrients and pesticides is reduced. The overall result is less soil erosion and improved water quality. Thus, management of crop residues is an integral part of many conservation tillage systems.

Rapid, accurate, and objective methods to quantify residue cover in individual fields are needed for management decisions. The standard technique for measuring crop residue cover used by the USDA Natural Resources Conservation Service (NRCS) is visual estimation along a line-transect (Morrison et al., 1993). Regional assessments of conservation tillage practices in the US are compiled from annual surveys of crop residue levels after planting by the Conservation Technology Information Center (CTIC, 2000). Reviews of crop residue measurement techniques document recent modifications and illustrate the unresolved problems of current techniques (Corak et al., 1993; Morrison et al., 1995).

The reflectance spectra of both soils and crop residue lack the unique spectral signature of green vegetation in the 400–1000 nm wavelength region (Aase & Tanaka, 1991; McMurtrey et al., 1993; Daughtry et al., 1995). Crop residues and soils are often spectrally similar and differ only in amplitude for visible and near infrared wavelengths (Baird & Baret, 1997; Streck et al., 2002), which makes discrimination between crop residues and soil difficult or nearly impossible using reflectance techniques. One promising approach for discriminating crop residues from soil is based on detecting a broad absorption feature near 2100 nm that appears in all compounds possessing alcoholic –OH groups, such as cellulose (Murray & Williams, 1988). Two other broad absorption features near 1730 and 2300 nm are associated primarily with nitrogen and lignin and may also serve as a basis to distinguish crop residues from soils (Curran, 1989; Elvidge, 1990; Kokaly & Clark, 1999). The absorption feature near 2100 nm is clearly evident in the reflectance spectra of the dry crop residues and is absent in

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doi:10.1016/j.rse.2003.10.023

the spectra of soils (Daughtry, 2001; Nagler et al., 2000; Streck et al., 2002). A new spectral variable, cellulose absorption index (CAI) that quantified the relative depth of this absorption feature was defined (Daughtry et al., 1996) using reflectance in three bands—two on the shoulders at 2021 and 2213 nm and one at 2100 nm (absorption maximum). However, this wavelength region is also strongly affected by water content (Palmer & Williams, 1974). Moisture content, age of the residue, and degree of decomposition affected the spectral reflectance and CAI of crop residues (Nagler et al., 2000). Water significantly altered the reflectance spectra of wet crop residues, but did not prevent the discrimination of crop residues from soils using CAI (Daughtry, 2001). Additional work is needed to determine the effects of mixed pixels (soil + residue) on discrimination of crop residues from soils and to test the CAI algorithm with hyperspectral images of fields and watersheds.

The objectives of this research were to (1) determine the spectral reflectance of crop residues and soils as a function of water content, and (2) assess the limits of discrimination that can be expected in mixed scenes. This research provides the scientific foundation required for assessing crop residue cover and tillage practices over large areas.

2. Materials and methods

2.1. Laboratory reflectance spectra

Reflectance spectra were acquired with a spectroradiometer (FieldSpec Pro, Analytical Spectral Devices, Boulder, CO) over the 400–2500 nm wavelength region at 1 nm intervals. The samples were illuminated by two 300-W quartz-halogen lamps mounted on the arms of a camera copy stand at 50 cm over the sample at a 45° illumination zenith angle. The 18° fore optic of the spectroradiometer was positioned 90 cm from the sample surface at a 0° view zenith angle which resulted in a 28 cm diameter field of view. The illumination and view angles were chosen to minimize shadowing and to emphasize the fundamental spectral properties of the soils and crop residues. Four spectra of 20 scans each were acquired from samples by rotating the sample tray 90° after each spectrum. A 61-cm square Spectralon reference panel (Labsphere, North Sutton, NH) was placed in the field of view, illuminated, and measured in the same manner as the samples. Reflectance factors were calculated and corrected for the non-ideal properties of the reference panel as described by Robinson and Biehl (1979). Mean reflectance spectra were plotted as a function of wavelength and moisture condition.

Broad absorption features near 1730, 2100 and 2300 nm in the reflectance spectra of the dry crop residues associated with nitrogen, cellulose, and lignin (Curran, 1989; Elvidge, 1990) were selected for continuum analysis (Kokaly & Clark, 1999; Clark, 1999). The continuum is an estimate of the reflectance spectrum without the absorption due to the compound of interest. Linear segments were used to approximate the continuum. The continuum-removed spectra were calculated by dividing the original reflectance values by the corresponding values of the continuum line (Kokaly & Clark, 1999). Band depths within each absorption feature were normalized by dividing by the band depth at the center of the feature. The cellulose absorption index (CAI), which is an adaptation of the continuum-removal method, was calculated as: $CAI = 0.5(R_{2.0} + R_{2.2}) - R_{2.1}$; where $R_{2.0}$, $R_{2.1}$, and $R_{2.2}$ are the reflectance values in 10 nm bands centered at 2015, 2106 and 2195 nm, respectively.

2.2. Soil and crop residue reflectance

Topsoil samples acquired for this study provided a range of colors (Table 1). Each soil was oven-dried at 105 °C for 48 h, crushed to pass a 2-mm screen, and placed to a depth of 0.5 cm in a 45-cm square sample tray that was painted flat black. Duplicate trays of each soil were prepared. After acquiring the spectral reflectance data from the oven-dried soils, the soils in the trays were saturated with water, allowed to drain freely for 2 h, and weighed before the spectral reflectance was measured again. Relative water content (RWC) was calculated as the water content divided by the maximum water content of each samples (i.e., RWC = 0.0 is oven-dry and RWC = 1.0 is saturated). The soils were dried as before and the measurement sequence was repeated.

Crop residues of corn (*Zea mays* L.) and soybean (*Glycine max* Merr.) were collected from agricultural fields near Beltsville, Maryland at 1 week and 8 months after harvest. The crop residues were dried at 70 °C for 48 h and then stored at room temperature. Spectral reflectance of intact dry crop residues were measured in 45-cm square sample trays filled to a depth of 3 cm. Duplicate trays of each residue were prepared. The samples and the trays then

Table 1
Soil names and sources of the top soils used in this study

Soil Series	Location	Classification	Munsell Color, wet	Munsell Color, dry
Barnes	Morris, MN	fine-loamy, mixed, superactive, frigid Calcic Hapludoll	Black 10 YR 2/1	Very dark gray 10 YR 3/2
Codorus	Beltsville, MD	fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudept	Dark brown 7.5 YR 3/2	Light yellowish brown 2.5 YR 6/4
Othello	Salisbury, MD	fine-silty, mixed, active, mesic Typic Endoaquult	Dark grayish brown 10 YR 4/2	Light brownish gray 10 YR 6/2

were placed in mesh bags, immersed in water for 2 h, allowed to drain freely for 2 h, and weighed before spectral reflectance was remeasured. The residues were dried as before and the measurement sequence was repeated.

Reflectance values of mixed scenes $R_{(M,\ \lambda)}$ with various proportions of crops residues and soils were simulated using linear combinations of the reflectance factors for crop residues and soils: $R_{(M,\ \lambda)} = R_{(S,\ \lambda)}(1 - f_R) + R_{(R,\ \lambda)}(f_R)$, where $R_{(S,\ \lambda)}$ and $R_{(R,\ \lambda)}$ are reflectance factors in waveband λ for soils and crop residues, respectively, and f_R is the fraction residue cover that ranged from 0 (100% soil) to 1.0 (100% crop residue). Scenarios for dry (RWC = 0) and wet (RWC = 1.0) mixtures of each residue and soil were simulated.

2.3. Field reflectance spectra

Reflectance spectra of mixtures of green vegetation, crop residues, and soils were acquired with the spectroradiometer over the 400–2500 nm wavelength region at 1 nm intervals. The 18° fore optics of the spectroradiometer and a 35-mm camera were mounted on a tripod at 1.2 m above the soil surface at a 0° view zenith angle. The diameter of the spectroradiometer field of view at the soil surface was 0.38 m. A 30-cm square Spectralon reference panel was mounted on a second tripod, placed in the field of view at 0.4 m from the optics, and measured in the same manner as the samples. Data were acquired under clear sky conditions on May 20 and 22, 2002 in various corn, soybean, and wheat fields near Beltsville, MD that had different tillage treatments. Reflectance factors were calculated (Robinson & Biehl, 1979). A photograph was acquired with each reflectance spectrum and the fractions of green vegetation, crop residue, and soil in the field of view of the spectroradiometer of each scene were determined visually using a dot-grid overlay (Williams, 1979). Random samples of the surface 2 cm of soil and crop residues were collected in each field. Moisture contents were determined after drying the soils at 105 °C for 48 h and the residues at 70 °C for 48 h.

3. Results and discussion

3.1. Lab spectra

Mean reflectance spectra of dry and wet corn and soybean residues are presented in Fig. 1. For each crop residue, the upper-most spectrum is the oven-dried residue and the lowest spectrum is for the water-saturated residue. The presence of water in the crop residue reduced reflectance across all wavelengths. Two major water absorption bands near 1450 and 1960 nm dominate the reflectance spectra at wavelengths >1300 nm. A broad absorption feature near 2100 nm is also evident in the reflectance spectra of all dry crop residues and is probably associated with lignin and cellulose in the crop residues (Murray & Williams, 1988).

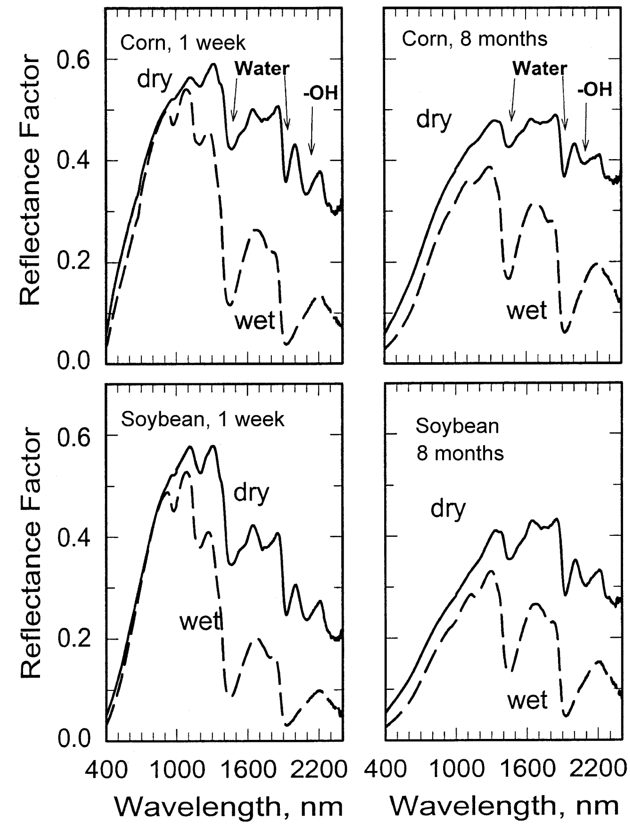

Fig. 1. Reflectance spectra of dry and wet corn and soybean residues at 1 week and 8 months after harvest.

Similar absorption bands in the reflectance spectra of dry, intact plant materials (Elvidge, 1990) and wheat residues (Streck et al., 2002) have also been observed.

Water reduced reflectance of the soils across all wavelengths, particularly for wavelengths >1300 nm (Fig. 2). The changes in reflectance associated with moisture were greater for the light-colored Othello soil than for the dark-colored Barnes soil. In addition to the two major water absorption features near 1450 and 1960 nm, a clay mineral absorption feature near 2200 nm (Baumgardner et al., 1985) is evident in all three soils, but is especially strong in the Codorus soil spectra. The broad cellulose-lignin absorption feature near 2100 nm is not evident in the spectra of the soils.

The effects of water absorption on the reflectance spectra gradually diminished as the water content of the crop residues decreased from water-saturated to oven-dry (Daughtry, 2001). Although the –OH absorption feature at 2100 nm was nearly obscured in the spectra of the water-saturated samples, Gao and Goetz (1994) showed that cellulose and lignin absorption features can be identified in reflectance spectra dominated by water.

The spectra of these crop residues and soils have similar shapes (Figs. 1 and 2). Crop residues may be brighter or darker than a particular soil depending on moisture content of the residue and the soil. Thus, discrimination of crop

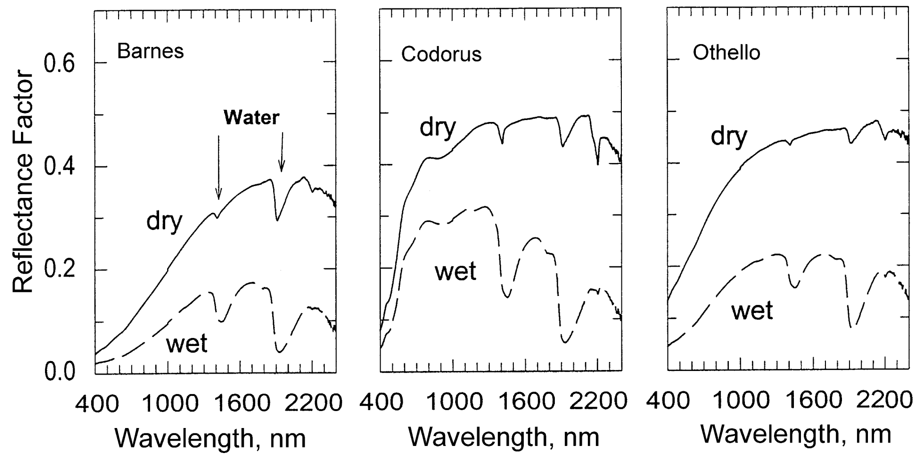

Fig. 2. Reflectance spectra of dry and wet Barnes, Codorus, and Othello soils.

residues from soils using reflectance in any single wavelength band in the 400–2400 nm wavelength region would be difficult and would require frequent adjustments of the discrimination thresholds for consistent results.

Changes in the fraction of crop residue cover produced differences in the simulated scene reflectance for the mixtures of dry crop residues and soils (Fig. 3). The wide range in reflectance factors for the spectra of mixtures of dry Barnes soil and dry corn residue made discrimination relatively easy at most wavelengths. For the dry Codorus and Othello soils, the addition of dry corn residue generally decreased reflectance across the spectrum. However, for the wet Barnes and Othello soils, the addition of wet corn residues increased the reflectance values of the mixed scenes across the spectrum (Fig. 4).

A closer examination of the 1600–2400 nm portion of the spectra (Figs. 5 and 6) showed the gradual shifts from the soil spectrum ($f_R = 0$) to the corn residue spectrum ($f_R = 1.0$) for each soil–residue mix. The depth of the mineral absorption feature centered near 2205 nm in each soil was attenuated by the corn residue absorption feature near 2100 nm (Fig. 5). Murphy (1995) examined the effects of green and dead vegetation on the depth, width, and asymmetry of mineral absorption features in the 2000–2400 nm wavelength region. Increasing amounts of green vegetation uniformly attenuated the mineral absorption features but did not affect the position of any mineral absorption feature. However, dead vegetation (e.g., crop residue) had distinct absorption features that significantly altered the mineral absorption features, particularly those located near 2200 nm (Murphy, 1995).

Water strongly attenuated both the cellulose-lignin feature near 2100 nm and the mineral absorption feature near 2200 nm (Fig. 6). The narrow range of reflectance values for the mixtures of wet soils and wet residues would reduce the accuracy of crop residue cover estimates. However, for dry and moist (RWC < 0.5), the wide range of CAI values should be adequate for assessing crop residue cover (Daughtry, 2001). Moisture conditions could be assessed using infrared reflectance as an indicator of water content (Murray

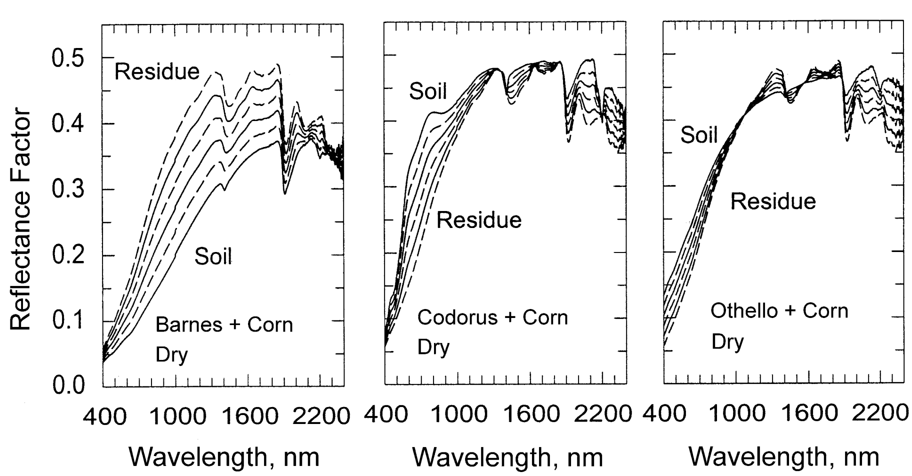

Fig. 3. Reflectance spectra of simulated mixed scenes of dry corn residue (8 months) and three dry soils. The six spectra for each soil represent 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of crop residue in the scene.

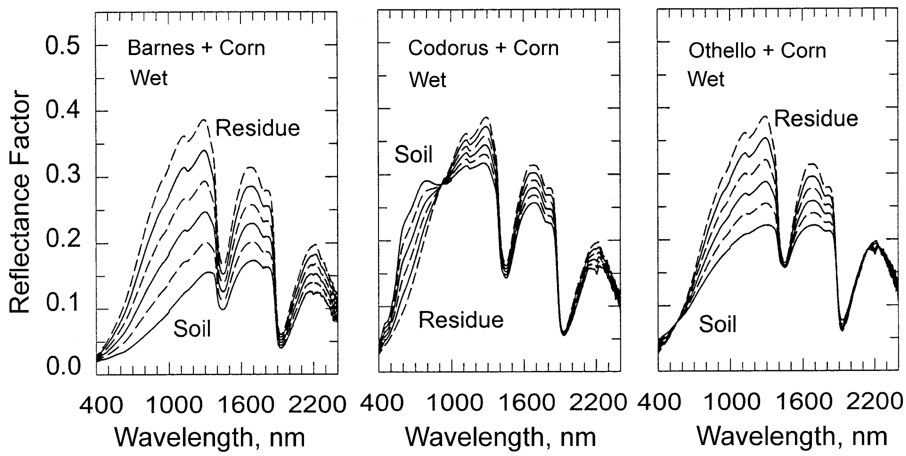

Fig. 4. Reflectance spectra of simulated mixed scenes of wet corn residue (8 months) and three wet soils. The six spectra for each soil represent 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of crop residue in the scene.

& Williams, 1988) and the expected range of CAI values determined (Daughtry, 2001; Streck et al., 2002).

The fundamental absorption band of many molecules occur in the wavelength region between 2500 and 15,000 nm (Murray & Williams, 1988). First, second, and third harmonics or overtones occur at approximately one-half, one-third, and one-fourth, respectively, of the wavelength of the fundamental absorption. However, the intensity of the each successive overtone absorption is much less intense than its previous one and low intensity overtones may be masked by high intensity overtones of different molecular types occurring in the same frequency range (Murray & Williams, 1988). Many chemical compounds found in plants have absorption features in the 1500–2500 nm wavelength region that are overtones of their fundamental absorptions. Three broad absorption features, centered near 1730, 2100 and 2300 nm, are primarily associated with nitrogen, cellulose, and lignin concentrations (Curran, 1989; Elvidge, 1990; Kokaly & Clark, 1999) and are illustrated for dry corn residues and two soils in Fig. 7.

Once the continuum lines were established, the continuum-removed spectra were calculated (Kokaly & Clark, 1999). For the dry crop residues, the continuum line was greater than the original reflectance and the continuum-removed reflectance was less than 1.0 (Fig. 8). For the dry soils, the continuum-removed reflectance was greater than 1.0. The absorption feature near 2100 nm became more prominent as residue was added to the bare soils. The cellulose absorption index (CAI) is an adaptation of the continuum-removal method that uses reflectance in three bands—two from the shoulders and one from the center—to estimate the depth of the absorption feature at 2100 nm. The continuum-removed reflectance (and CAI) provided better separation of crop residues from soils than reflectance factors because the crop residues could be darker or lighter than the soil (Figs. 5 and 6).

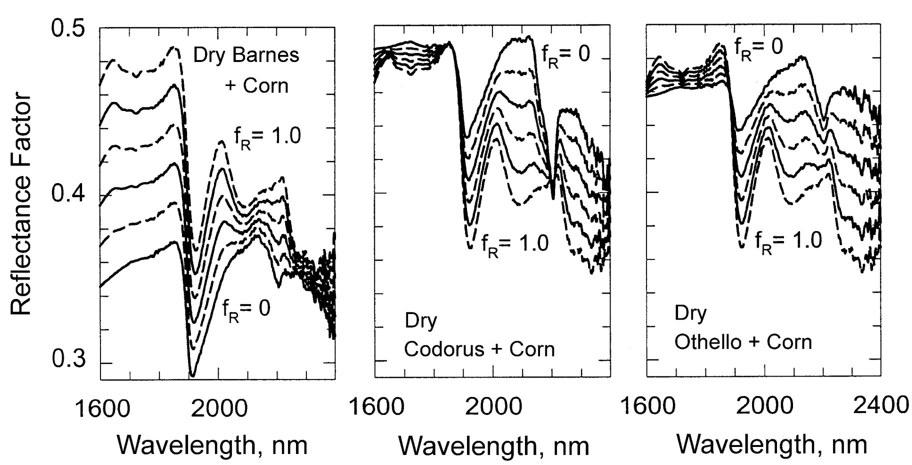

Fig. 5. Expanded scale of reflectance spectra of simulated mixed scenes of dry corn residue (8 months) and three dry soils. The six spectra for each soil represent 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of crop residue in the scene.

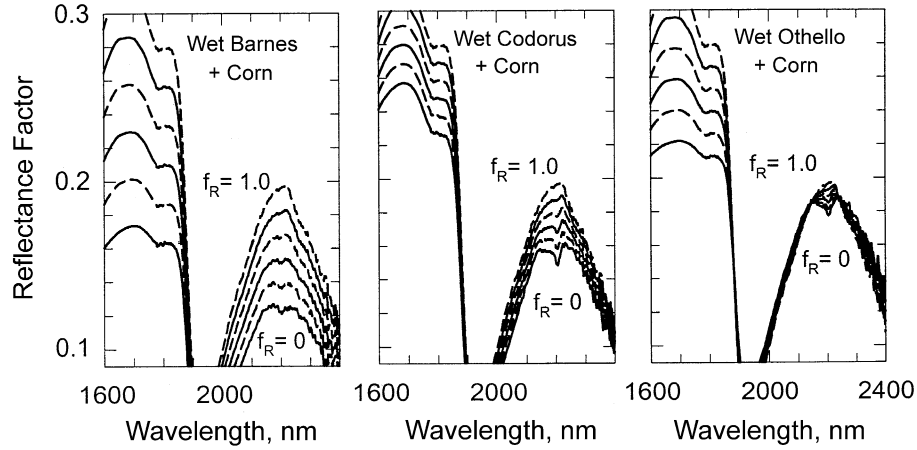

Fig. 6. Expanded scale of reflectance spectra of simulated mixed scenes of wet corn residue (8 months) and three wet soils. The six spectra for each soil represent 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of crop residue in the scene.

3.2. Field spectra

Representative reflectance spectra of mixtures of crop residues, green vegetation, and soil acquired along transects in corn fields near Beltsville, MD are shown in Fig. 9 and the fractions of each component are presented in Table 2. The breaks in the reflectance spectra near 1950 nm were associated with the strong absorption of solar radiation by water in the atmosphere and the scene. Mean water content (weight basis) was 8.1% for the soil and 7.7% for the residues.

This collection of spectra also illustrated the variability in the reflectance spectra that occurred within the fields (Fig. 9). The cellulose-lignin absorption feature near 2100 nm is clearly evident in the corn residue spectrum (Fig. 9, curve D) but absent in the bare soil (curve A) and green vegetation (curve F) spectra. The clay mineral absorption feature near 2200 nm is also evident in spectra of curves A, B and C, which represent soil fractions of 0.97, 0.81 and 0.61, respectively (Table 2). Shadows and variations in soil and residue reflectance from scene to scene contributed to the wide range of values across all wavelengths. The change in reflectance factor in the 400–2400 nm wavelength region is not consistently related to the changes in fractional crop residue cover. For example, the reflectance factor of the scene with $f_R = 0.19$ (Fig. 9, curve B) was higher than the reflectance factor of either the corn residue (curve D; $f_R = 1.0$) or the soil (curve A; $f_R = 0.03$). However, the relative depth of the cellulose-lignin feature, as measured by CAI, was largely independent of reflectance factor and was linearly related with fraction crop residue cover (Table 2).

Because water is the primary absorber in the shortwave infrared region, the high moisture content of green vegetation significantly attenuated the reflectance signal from the absorption features as expected (Murphy, 1995). The reflectance spectrum of wet cotton cellulose closely resembles the spectrum of a green leaf from 800 to 2500 nm (Elvidge,

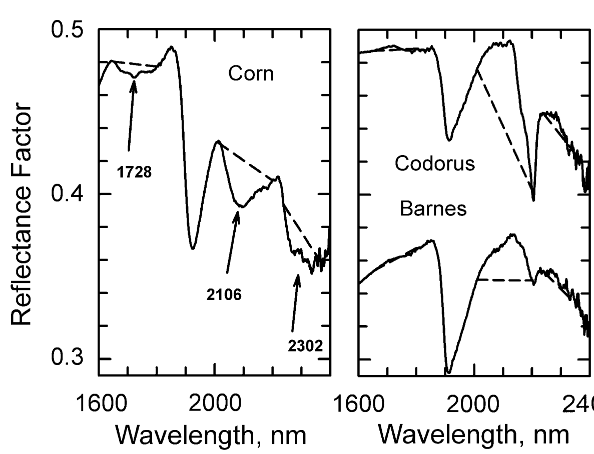

Fig. 7. Linear continua for three major absorption features in corn residues. The same lines are also shown on the spectra of two soils.

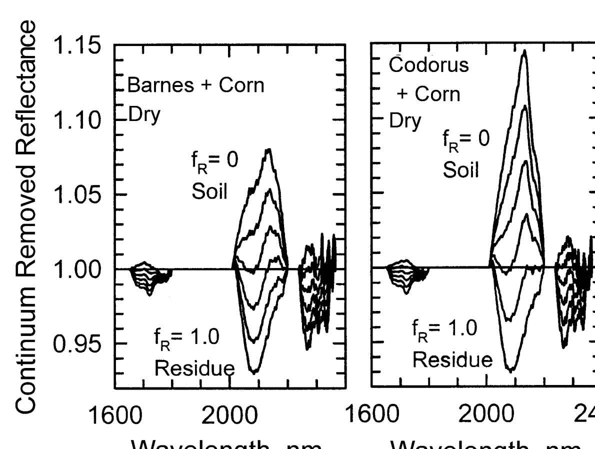

Fig. 8. Continuum-removed reflectance spectra for Barnes and Codorus soils with 0, 0.2, 0.4, 0.6, 0.8, and 1.0 fractions of corn residue cover in the scene.

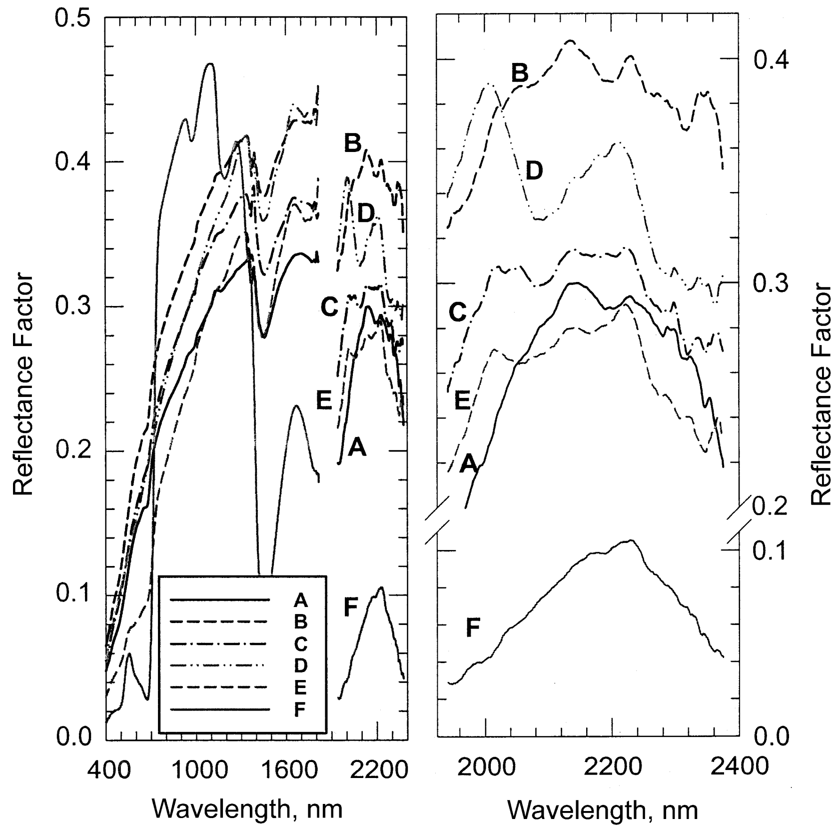

Fig. 9. Reflectance spectra of selected scenes in corn fields. The letters in the legend correspond to the descriptions (Table 2) of each scene.

1990). The green vegetation spectra (Fig. 9; curve F) is remarkably similar in shape and amplitude to the spectra of wet crop residues in the 2000–2400 nm wavelength region (Figs. 1 and 6).

Crop residue cover was linearly related to CAI (Fig. 10, left), but not to NDVI (not shown). Small fractions of green vegetation in the scene had little effect on the overall linear relationship in Fig. 10, left, but as the fraction of green vegetation in the scene increased, the errors for estimating crop residue cover using CAI increased. Water in green vegetation attenuated the cellulose-lignin absorption feature and reduced the CAI value in a similar manner that water reduced the CAI values of crop residues (Daughtry, 2001). Green vegetation cover was linearly related to NDVI (Fig. 10, right), but not to CAI (not shown). If scenes with green vegetation fractions >0.3 are excluded, the coefficient of determination (r^2) for predicting fraction of residue cover improves to 0.89 and the RMSE decreases to 0.103.

The Conservation Technology Information Center (CTIC) has defined conservation-tillage as any tillage and planting system that has more than 30% residue cover after planting; reduced-tillage as15–30% residue cover; and intensive or conventional tillage as less than 15% residue cover (CTIC, 2000). In Fig. 11, CAI and NDVI were plotted together and secondary axes for the fraction of residue cover and fraction of green vegetation cover were added. The two horizontal dashed lines in Fig. 11 divide the feature space into tillage classes based on crop residue cover. Scenes with more than 30% green vegetation cover (right of vertical dashed line) have NDVI values greater than bare soil or crop residue, but have low CAI values characteristic of low residue cover. Determining the tillage category of vegetated scenes from these spectral indices will require additional information about the cropping practices.

Conventional tillage accelerates soil erosion by increasing the soil's exposure to wind and rain and hastens carbon oxidation by increasing soil aeration, soil temperature, and soil-residue contact. Long-term use of conservation tillage practices can lead to increased soil organic carbon, improved soil structure, and increased aggregation compared with plow-tilled soils (Rasmussen & Rohde, 1988). Ecosys-

Table 2
Fractions of green vegetation (f_{Green}), crop residue ($f_{Residue}$), and soil (f_{Soil}) for the spectra shown in Fig. 9

Spectrum	f_{Green}	$f_{Residue}$	f_{Soil}	CAI	NDVI
A	0.0	0.03	0.97	−2.05	0.176
B	0	0.19	0.81	−0.93	0.152
C	0	0.39	0.61	1.18	0.152
D	0	1.00	0	4.43	0.143
E	0.15	0.58	0.27	0.55	0.339
F	0.98	0.01	0.01	−0.81	0.866

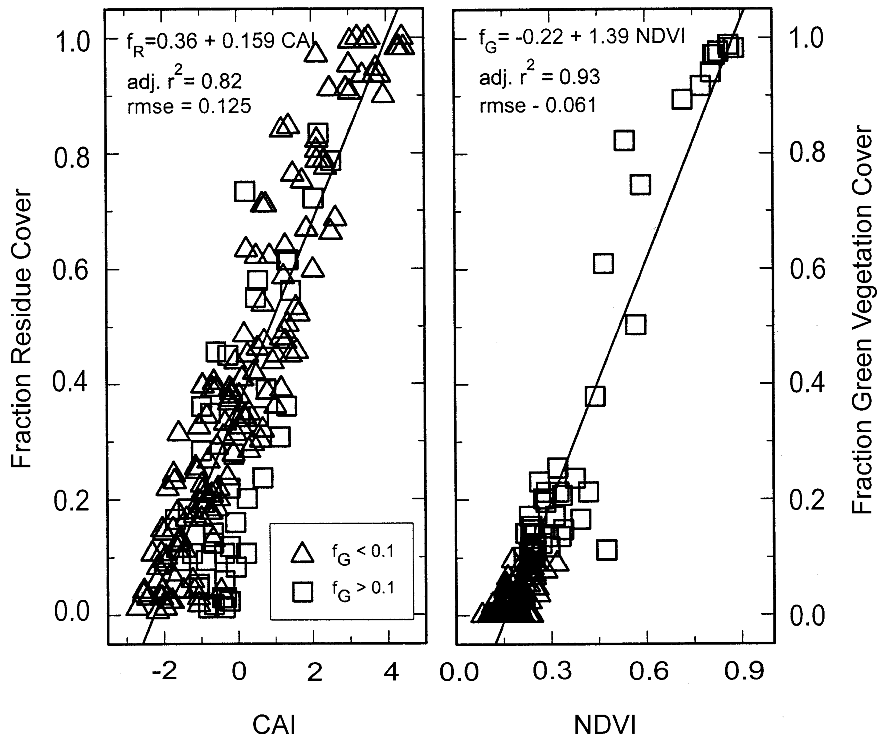

Fig. 10. Scatter plots of (left) fraction of residue cover vs. CAI and (right) fraction green vegetation cover vs. NDVI for corn, soybean, and wheat fields.

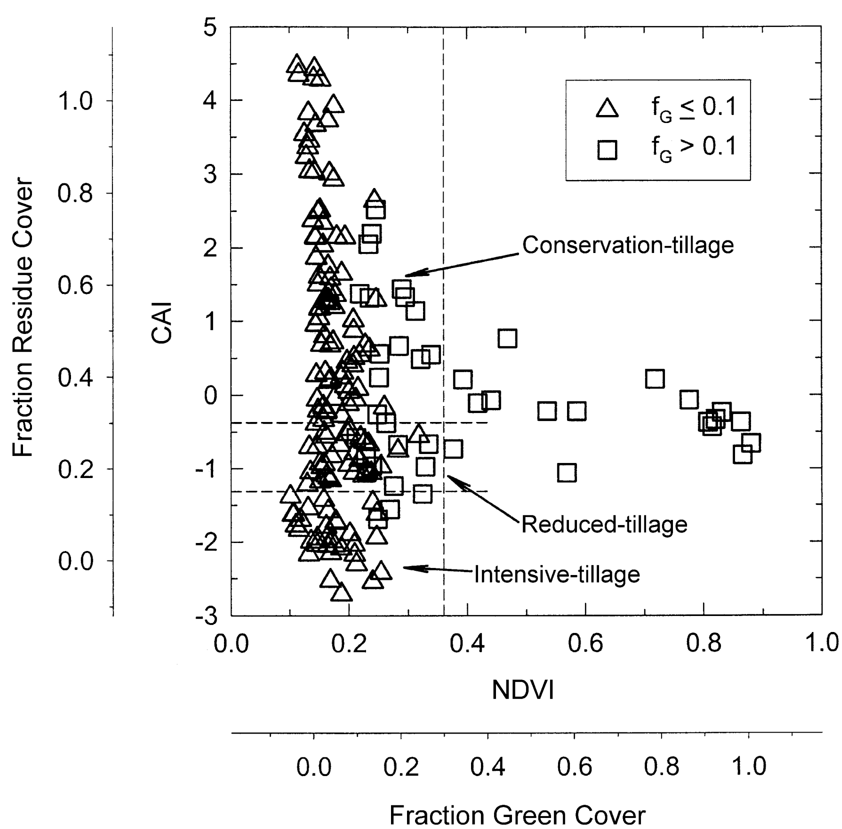

Fig. 11. Scatter plot of CAI and NDVI for 186 scenes in corn, soybean and wheat fields. Horizontal dashed lines at 0.15 and 0.30 fractions of residue cover divide the feature space into three tillage categories.

tem models require information on tillage practices to reliably describe C and N dynamics in agricultural fields (Ma & Shaffer, 2001).

The capability to categorize tillage using remotely sensed images could be crucial input for assessing spatial variability of carbon dynamics across agricultural landscapes. Efforts to identify tillage practices using changes in surface reflectance have had mixed success (e.g., Baird & Baret, 1997; DeGloria et al., 1986; van Deventer et al., 1997). However, if tillage categories are defined by the amount of residue cover on the soil, it may be possible to identify these categories of tillage practices using CAI and NDVI as illustrated in Fig. 11. An imaging sensor that included the two NDVI bands and the three CAI bands could acquire spectral and spatial data for assessing tillage practices in many fields. Both the airborne imaging spectrometer AVIRIS (Airborne Visible Infrared Imaging Spectrometer) and the proof-of-concept space-borne imaging spectrometer Hyperion have the required bands, but have not yet been evaluated for this application. Regional surveys of soil conservation practices which affect soil carbon dynamics may be feasible using advanced multispectral or hyperspectral imaging systems.

Acknowledgements

We are indebted to Andrew Russ and Adam Booher who acquired and processed much of the data used in this paper.

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